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# EXCITED STATES OF BARIUM 136 AND BARIUM 134

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*Cleveland, Ohio*



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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## ABSTRACT

Sources of 9.87-minute lanthanum 136 and 6.82-minute lanthanum 134 were made by bombarding enriched barium 136 and barium 134 with 10-MeV protons. A 20-cubic-centimeter lithium-drifted germanium detector was used to observe the gamma rays emitted by lanthanum 136 and lanthanum 134. The energies and relative intensities of these gamma rays were measured. The results suggest the existence of excited states of barium 136 at 818.5, 1578.9, 2080.2, 2128.5, 2141.0, and 2315.6 keV, and excited states of barium 134 at 604.7, 1168.2, 2159.7, 2336.4, 2489.3, 2565.1, 2599.9, and 2693.3 keV.

# EXCITED STATES OF BARIUM 136 AND BARIUM 134

by Glenn M. Julian\* and Theodore E. Fessler

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## SUMMARY

Sources of 9.87-minute lanthanum 136 ( $^{136}\text{La}$ ) and 6.82-minute lanthanum 134 ( $^{134}\text{La}$ ) were made by the (p, n) reaction on enriched barium 136 ( $^{136}\text{Ba}$ ) and barium 134 ( $^{134}\text{Ba}$ ). A 20-cubic-centimeter lithium-drifted germanium (Ge(Li)) detector was used to observe the gamma rays emitted by these sources. The energies in keV (with relative intensities in parentheses) of gamma rays emitted in the decay of  $^{136}\text{La}$  are 760.4 (14.3), 818.5 (100), 1019.1 (5.6), 1261.7 (1.3), 1310.5 (4.5), 1322.5 (13.0), 1497.1 (2.1), 2127.7 (1.7), and annihilation radiation (3090). The energies in keV (with relative intensities in parentheses) of gamma rays emitted in the decay of  $^{134}\text{La}$  are 563.5 (6.7), 604.7 (100), 1168.9 (2.6), 1211.0 (2.4), 1321.1 (2.4), 1424.1 (3.9), 1482.4 (2.3), 1555.0 (8.6), 1731.7 (4.9), 1960.4 (2.0), 1995.2 (1.4), 2088.6 (0.8), and annihilation radiation (2200). These results suggest the existence of excited states of  $^{136}\text{Ba}$  at 818.5, 1578.9, 2080.2, 2128.5, 2141.0, and 2315.6 keV and excited states of  $^{134}\text{Ba}$  at 604.7, 1168.2, 2159.7, 2336.4, 2489.3, 2565.1, 2599.9, and 2693.3 keV. The level schemes of  $^{136}\text{Ba}$  and  $^{134}\text{Ba}$  are compared with those of similar nuclei. Arguments are given to suggest that the previously unknown second excited state of  $^{136}\text{Ba}$  has spin and parity of  $2^+$ .

An important parameter for the description of near-spherical, even-even nuclei, such as  $^{136}\text{Ba}$  and  $^{134}\text{Ba}$  are assumed to be, is  $B(E2; 2^{+'} \rightarrow 0^+)/B(E2; 2^{+'} \rightarrow 2^+)$ , the ratio of the reduced transition probabilities for the deexcitation modes of the second  $2^{+'}$  excited state ( $2^{+'}$ ). In this study, this ratio has been measured to be  $0.005 \pm 0.001$  for  $^{134}\text{Ba}$ . No transition is observed from the second excited state of  $^{136}\text{Ba}$  to the ground state. If the second excited state is  $2^+$ , an upper limit on the ratio  $B(E2; 2^{+'} \rightarrow 0^+)/B(E2; 2^{+'} \rightarrow 2^+)$  can be set at 0.0004.

No evidence is found to indicate that either  $^{136}\text{Ba}$  or  $^{134}\text{Ba}$  possesses all three members of a possible "vibrational triplet" of states at about twice the energy of the first excited state.

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## INTRODUCTION

The nature of the low-lying energy levels in near-spherical, even-even nuclei is not well understood. If these nuclei are assumed to undergo nearly harmonic quadrupole shape vibrations, the second vibrational mode with two phonons present should consist of a close-lying  $0^+ - 2^+ - 4^+$  triplet at about twice the energy of the one-phonon first excited state. However, among near-spherical nuclei with proton number  $Z > 50$ , only tellurium 122 has been found to have all three of these predicted states (refs. 1 to 3 and private compilation). Also for many of these nuclei a crossover transition from the second excitation to the ground state is observed. Such a transition would be forbidden for purely harmonic oscillations; in fact, it is weak compared with the transition from the second excitation to the first excitation. The occurrence of the crossover transition may be due to slight anharmonicity in the vibrations.

The present experimental study of the beta decay of  $^{136}\text{La}$  and  $^{134}\text{La}$  was undertaken to clarify understanding of the low-lying excited states of the daughter nuclei,  $^{136}\text{Ba}_{80}$  and  $^{134}\text{Ba}_{78}$ . Both of these barium nuclei are believed to be nearly spherical because of their nearness to the closed shells at 50 protons and 82 neutrons. If the  $0^+$  and  $2^+$  triplet members exist, their population in the decay of  $1^+ ^{136}\text{La}$  and  $1^+ ^{134}\text{La}$  would be allowed by beta-decay selection rules. Only the  $\approx 820$ -keV first excited state of  $^{136}\text{Ba}$  had previously been reported (ref. 4) to be populated in the decay of  $^{136}\text{La}$ , so a search was made for possible states at about twice this energy. The region of the second excited state of  $^{134}\text{Ba}$  was also reexamined, although a recent study (ref. 5) of the beta decay of  $^{134}\text{La}$  yielded no evidence for the existence of a possible  $0^+$  second excited state of  $^{134}\text{Ba}$ .

## EXPERIMENTAL PROCEDURE

### Source Preparation

The sources of  $^{136}\text{La}$  and  $^{134}\text{La}$  were prepared by the (p, n) reaction on enriched  $^{134}\text{Ba}$  and enriched  $^{136}\text{Ba}$ . The isotopic composition of these targets is given in table I. A 1-microampere beam of 10-MeV protons from the Lewis Research Center Cyclotron was used in bombardment. Most of the sources were prepared from barium nitrate targets. In these, the contaminants, 20.5-minute carbon 11, 10-minute nitrogen 13, and 71-second oxygen 14, were formed. All three contaminants emit positrons; the oxygen 14 ( $^{14}\text{O}$ ) also emits a 2.31-MeV gamma ray. These three activities were the only contaminants observed.

To study the annihilation radiation from the La isotopes, it was necessary to eliminate the positron-emitting contaminants. Before bombardment the target material

TABLE I. - ISOTOPIC COMPOSITIONS OF  
ENRICHED BARIUM TARGETS

Atomic weight of barium isotope	$^{134}\text{Ba}$ target	$^{136}\text{Ba}$ target
	Composition, at. %	
130, 132	< 0.1	< 0.5
134	84.6	.07
135	4.1	.81
136	1.78	92.9
137	1.63	1.75
138	7.9	4.54

was converted to anhydrous barium chloride. This was done by dissolving the barium nitrate in water, adding sodium carbonate solution to form a barium carbonate precipitate, dissolving the precipitate in hydrochloric acid, and evaporating to dryness to form barium chloride. To drive off water of hydration, the barium chloride was heated before bombardment, and it was placed in the cyclotron vacuum before it could cool and reabsorb atmospheric water. After the bombardment, lanthanum activities were separated by dissolving the barium chloride in water, adding lanthanum carrier, and precipitating lanthanum oxalate with an equal volume of a hot solution consisting of 10-percent oxalic acid in 1.5 N hydrochloric acid. This procedure eliminated all activities other than lanthanum activities.

## Equipment

The gamma-ray spectrometer consisted of a 20-cubic-centimeter lithium-drifted germanium detector, a low-noise pulse amplifier, and a 4096-channel pulse-height analyzer. This system had an energy resolution of approximately 6 keV for 1-MeV gamma rays.

## Data Analysis

Digital computer codes were used to plot and analyze all the pulse-height spectra. The method of least squares (ref. 6) was used to determine intensities, energies, and half-lives of gamma-ray peaks, as well as the statistical uncertainties in each of these quantities.

Plots of the pulse-height spectra were examined to find gamma-ray peaks and to estimate their intensities and channel-number locations. Then the spectra were analyzed by using these estimates as input to a least-squares fitting of peaks, Compton edges, and a background continuum to data. From these fits, best estimates were obtained for the peak intensities and locations and also for the uncertainties in these two quantities.

The functions used in the least-squares fitting were obtained by folding the expected electron energy spectrum into the response functions of the detector-amplifier system and the pulse-height analyzer. The electron energy spectrum of photopeaks was assumed to be a delta function at the full gamma-ray energy. The spectrum of Compton edges was obtained from the Klein-Nishina formula for the number-energy distribution (ref. 7) by expanding that equation about the edge energy and dropping all but the first two terms in the expansion. The response function of the detector-amplifier system was assumed to be Gaussian, and the pulse-height analyzer was assumed to have perfectly sharp channel edges.

The energies of gamma rays were determined from the peak locations and a calibration equation. Constants in the calibration equation were determined for each pulse-height spectrum by a least-squares fit of peak locations to known peak energies. In some cases the known energies were of gamma rays from calibrating sources counted simultaneously with the lanthanum activity. Table II lists the isotopes and gamma-ray energies that were used as calibration standards (refs. 8 and 9, and an unpublished 1966 compilation by J. B. Marion, University of Maryland, College Park, Maryland). In other cases the known energies were of annihilation radiation and of strong gamma

TABLE II. - STANDARDS USED IN ENERGY CALIBRATION

Standard	Gamma-ray energy, keV
Annihilation radiation <sup>a</sup>	511.006±0.002
<sup>b</sup> Cesium 137	661.595±0.076
<sup>c</sup> Cobalt 56	846.85±0.1
	1037.88±0.1
	1238.14±0.1
	1360.34±0.1
	1771.62±0.1
<sup>c</sup> Yttrium 88	2598.7±0.2
	898.2±0.18
	1836.2±0.2

<sup>a</sup>From unpublished compilation by J. B. Marion, Univ. of Maryland, 1966.

<sup>b</sup>From ref. 8.

<sup>c</sup>From ref. 9.

rays from the lanthanum isotopes, for which energies had already been determined by simultaneously counting with the standard sources.

A third-order power series in channel location was used for the energy calibration equation. Experience has shown that this gives a satisfactory fit for spectra of sources whose energies have been very accurately determined by others. Uncertainties in the barium gamma-ray energies arise from uncertainties in the standard energies (table II) and from statistical uncertainties in the locations of both the standard and the unknown photopeaks. Each of these sources of error has been estimated, and their combined effects are included in the tabulated results.

Relative gamma-ray intensities were obtained from the pulse-height spectrum peak intensities by correcting for the photopeak efficiency of the Ge(Li) detector. Figure 1 shows the energy dependence of the relative photopeak efficiency of the detector used in this investigation. The data points in figure 1 were obtained by comparing the measured relative peak intensities from a particular isotope to the relative gamma-ray intensities reported in the literature for that isotope. Several isotopes were used (refs. 3 and 9 to 11); the data for each isotope were normalized to obtain a smooth curve over the entire energy range. It is estimated that, from this curve, the relative photopeak-detection efficiency may be determined to  $\pm 10$  percent for a given photopeak energy. The error quoted on the relative gamma-ray intensities is the result of both the statisti-

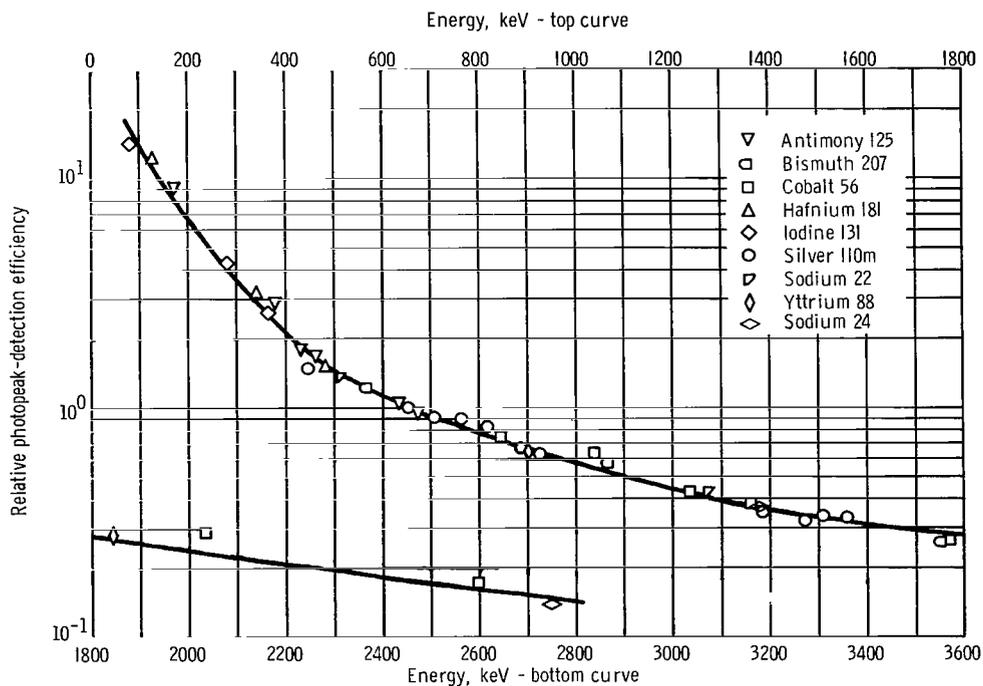


Figure 1. - Empirical relative-photopeak-detection-efficiency curve for the 20-cubic-centimeter Ge(Li) detector. Actual relative gamma-ray intensities were obtained from references 3 and 9 to 11.

cal uncertainty of the peak intensity and the use of the relative-photopeak-detection-efficiency curve.

Experiment showed that for the range of energies investigated (approx. 100 to 3500 keV), the relative photopeak efficiency of the detector was essentially independent of solid angle for source-to-detector distances of 10 centimeters or more. As a consequence, it was possible to count a source for several half-lives by moving it closer and closer to the detector as its intensity decreased, as long as it was no closer than 10 centimeters from the detector.

Half-lives of the La isotopes were measured using chemically purified sources. First, the sample material was placed in a thick plastic absorber so all the positrons emitted would annihilate close to their source. Then, with the source position fixed, spectra were recorded for several successive intervals of equal duration (4 minutes for  $^{134}\text{La}$  and 8 minutes for  $^{136}\text{La}$ ). The half-lives of the La isotopes were determined by least-squares analysis of the time dependence of the gamma-ray peak intensities. In this analysis the time duration of recording each spectrum was taken to be that measured by the "live time" clock of the pulse-height analyzer. The mean time of each interval, determined from a "real time" clock, was used to represent the time at which the corresponding spectrum was taken. Uncertainties reported for the half-lives are those caused by statistical uncertainties in the peak intensities and in the spectrometer live time.

## RESULTS AND LEVEL SCHEME FOR BARIUM 136

Figure 2 shows a gamma-ray spectrum of  $^{136}\text{La}$  obtained by adding spectra of seven sources made in successive bombardments of barium nitrate ( $^{136}\text{Ba}(\text{NO}_3)_2$ ). For each the bombardment lasted 10 minutes and counting began approximately 4 minutes later. The 2312.5-keV peak and the associated double-escape peak from the contaminating  $^{14}\text{O}$  are indicated in parentheses. Relative intensities of all gamma rays except annihilation radiation were determined from this spectrum. The relative intensity of the  $^{136}\text{La}$  annihilation radiation was determined in a separate experiment in which the target material was anhydrous barium chloride ( $^{136}\text{BaCl}_2$ ) so that the positron-emitting contaminants were not produced. The relative intensities of the  $^{136}\text{La}$  gamma rays are given with the gamma-ray energies in table III.

An interesting feature of the spectrum of figure 2 is the intensity of the continuum at approximately 1000 keV; it is significantly greater than the intensity of the continuum above the 1019.1-keV photopeak. Since the observed photopeaks cannot give rise to Compton edges in this region, the most probable explanation is that there are at least two unresolved weak gamma rays with energies near 1000 keV. Figure 3 shows the

TABLE III. - ENERGIES AND RELATIVE INTENSITIES OF GAMMA RAYS FROM  $^{136}\text{Ba}$

Energy, keV	Relative intensity
<sup>a</sup> 511.006±0.002	3090.0±430.0
760.4±0.2	14.3±2.1
818.5±0.2	100.0
<sup>b, c</sup> 997.3±0.6	2.0±0.4
<sup>b, c</sup> 1010.5±0.5	2.9±0.5
<sup>c</sup> 1019.1±0.3	5.6±0.9
1261.7±0.8	1.3±0.3
1310.5±0.5	4.5±0.8
1322.5±0.4	13.0±1.9
1497.1±0.7	2.1±0.4
2127.7±0.7	1.7±0.3

- <sup>a</sup>Annihilation radiation. Energy value adopted from unpublished compilation by J. B. Marion, Univ. of Maryland.
- <sup>b</sup>Existence of this gamma ray is uncertain.
- <sup>c</sup>Not placed in level scheme of fig. 4.

TABLE IV. - MEASURED HALF-LIVES OF GAMMA RAYS FROM  $^{136}\text{La}$  AND  $^{134}\text{La}$

Parent nucleus	Gamma-ray energy, keV	Half-life, min
$^{136}\text{La}$	511.0	9.874±0.023
	760.4	8.97±0.075
	760.4	8.8±1.4
	818.5	9.73±0.18
	818.5	10.35±0.33
	Weighted average	9.87±0.02
$^{134}\text{La}$	511.0	6.72±0.09
	604.7	7.28±0.30
	604.7	6.99±0.18
	Weighted average	6.82±0.08

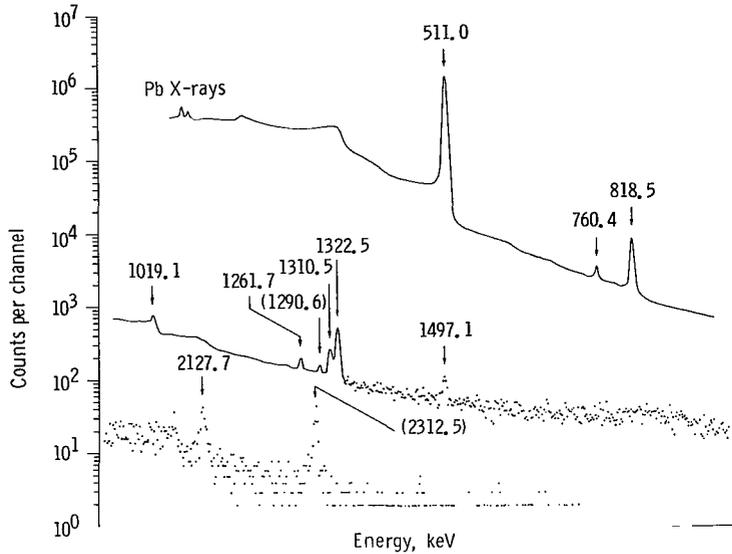


Figure 2. - Gamma-ray spectrum of  $^{136}\text{La}$ . Peaks due to the contaminating  $^{140}\text{O}$  are indicated in parentheses. The energy scale graduation has been omitted and the spectrum folded twice to reduce length. Individual data points are replaced by a smooth line in part of the spectrum.

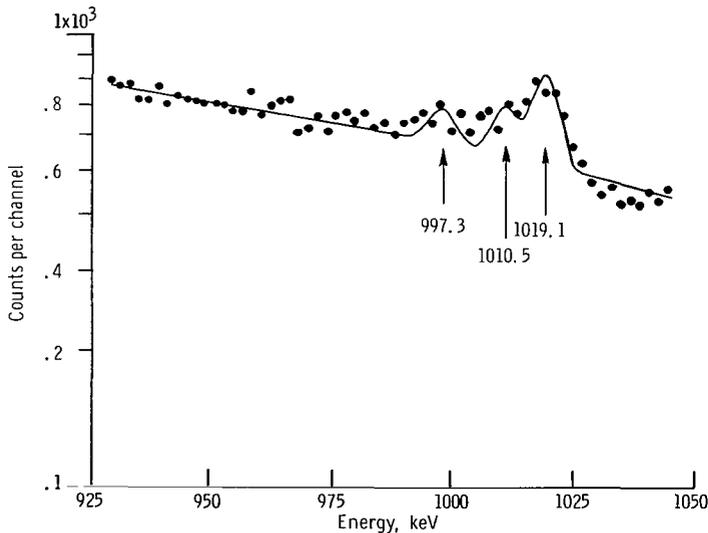


Figure 3. - Detail of spectrum of figure 2, showing least-squares fit of three peaks to data near 1000 keV.

least-squares fit obtained when the computer is instructed to fit three peaks of energy near 1000 keV to the data shown in figure 2. The resulting peak energies and relative intensities are included in table III.

The decay of  $^{136}\text{La}$  was followed primarily to verify the purity of the source. The gamma rays of 511.0-, 760.4-, and 818.5-keV energy were sufficiently intense that least-squares analysis of the time dependence of their intensities could be performed. Measured values for the half-lives of these peaks are given in table IV. The weighted average of these values,  $9.87 \pm 0.02$  minutes, is adopted as the half-life of  $^{136}\text{La}$ .

The short half-life of  $^{136}\text{La}$  and the weakness of the high-energy gamma rays make NaI(Tl)-Ge(Li) gamma-gamma coincidence experiments on  $^{136}\text{La}$  impractical with present gamma-gamma coincidence efficiencies. Nevertheless, much can be deduced about excited states of  $^{136}\text{Ba}$  populated in the decay of  $^{136}\text{La}$ . The energy sum rule and the value (ref. 4) of  $2.87 \pm 0.07$  MeV for the energy available in the decay of  $^{136}\text{La}$  to  $^{136}\text{Ba}$  are used. Conjectures about the lowest-lying states may be based on the systematics of nearby even-even nuclei. Excited states of  $^{136}\text{Ba}$  are deduced to exist at  $818.5 \pm 0.2$ ,  $1578.9 \pm 0.3$ ,  $2080.2 \pm 0.8$ ,  $2128.5 \pm 0.4$ ,  $2141.0 \pm 0.5$ , and  $2315.6 \pm 0.7$  keV. These states, together with the transitions between them, are shown in the level scheme in figure 4. Except for the three gamma rays of energy near 1000 keV, all gamma rays observed in the decay of  $^{136}\text{La}$  have been fitted into this scheme. The log ft values and relative intensities of the transitions from  $^{136}\text{La}$  were calculated from the

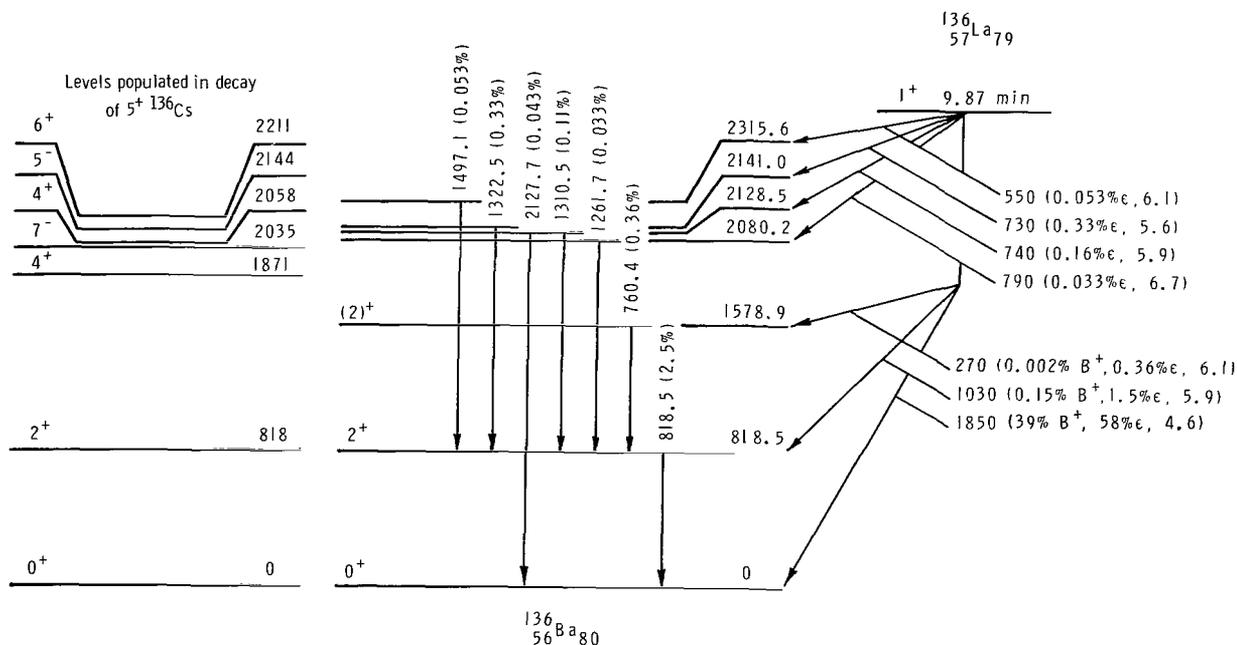


Figure 4. - Proposed level scheme of  $^{136}\text{Ba}$ . Energies are given in keV. Intensities of gamma rays and of beta-decay branches are given in percentage of  $^{136}\text{La}$  decays.

intensities of the gamma rays (table III) and the maximum beta-ray energy (ref. 4). For each of the levels populated by positron emission, the intensity ratio of K-electron capture to positron emission was assumed to be the value obtained theoretically for allowed beta decay (ref. 12). Capture of electrons from higher shells was assumed to be 10 percent of that from the K shell (ref. 13).

Existence of the levels at 818.5, 1578.9, and 2080.2 keV is consistent with results obtained by G. C. Morrison of the Argonne National Laboratory (private communication) in studying the (d, p) reaction on  $^{135}\text{Ba}$ . However, the present experiment has revealed no evidence that the decay of  $^{136}\text{La}$  populates a level of  $^{136}\text{Ba}$  at about 1550 keV, which Morrison found to be strongly excited in the (d, p) reaction on  $^{135}\text{Ba}$  and possibly weakly excited in the (d, d') reaction on  $^{136}\text{Ba}$ . If the 1550-keV level were populated in the decay of  $^{136}\text{La}$ , a 730-keV transition might be expected between this level and the first excited state of  $^{136}\text{Ba}$ ; from the statistics in the spectrum of figure 2, an upper limit on the intensity of 730-keV gamma rays can be set at 0.025 percent of  $^{136}\text{La}$  decays. Furthermore, no evidence was found to indicate that the decay of  $^{136}\text{La}$  populates a 1.4-MeV level of  $^{136}\text{Ba}$ , whose possible existence was deduced (ref. 3) from neutron capture data. For comparison, figure 4 shows the levels of  $^{136}\text{Ba}$  populated in the decay of  $5^+$  cesium 136 ( $^{136}\text{Cs}$ ) (refs. 14 and 15).

## RESULTS AND LEVEL SCHEME FOR BARIUM 134

Figure 5 shows a gamma-ray spectrum of  $^{134}\text{La}$  obtained by adding spectra of seven sources made in successive bombardment of  $^{134}\text{Ba}(\text{NO}_3)_2$ . For each the bombardment lasted 5 minutes and counting began approximately 4 minutes later. Peaks due to the contaminating  $^{14}\text{O}$  are indicated in parentheses. Gamma rays from the 1.78-percent  $^{136}\text{Ba}$  content of the target were too weak to be seen. Relative intensities of all gamma rays except annihilation radiation were determined from this spectrum. The relative intensity of the  $^{134}\text{La}$  annihilation radiation was determined in a separate experiment in which the target material was anhydrous  $^{134}\text{BaCl}_2$  so that the positron-emitting contaminants were not produced. The relative intensities and energies of the gamma rays from  $^{134}\text{La}$  are given in table V. All the gamma rays observed in a previous study (ref. 5) of the decay of  $^{134}\text{La}$  were observed. However, several uncertain peaks in the earlier spectra can be identified as photopeaks in the spectrum of figure 5. They stand out more clearly above the continuum because of the larger photopeak-detection efficiency of the detector used in the present investigation. No evidence was found for the existence of weak gamma rays of 548- and 572-keV energy that Gönö, et al., (ref. 16) reported in the decay of  $^{134}\text{La}$ .

The decay of the  $^{134}\text{La}$  source was followed, but only the annihilation radiation and the 604.7-keV gamma ray were sufficiently intense that values for their half-lives could

TABLE V. - ENERGIES AND RELATIVE INTENSITIES OF GAMMA RAYS FROM  $^{134}\text{La}$

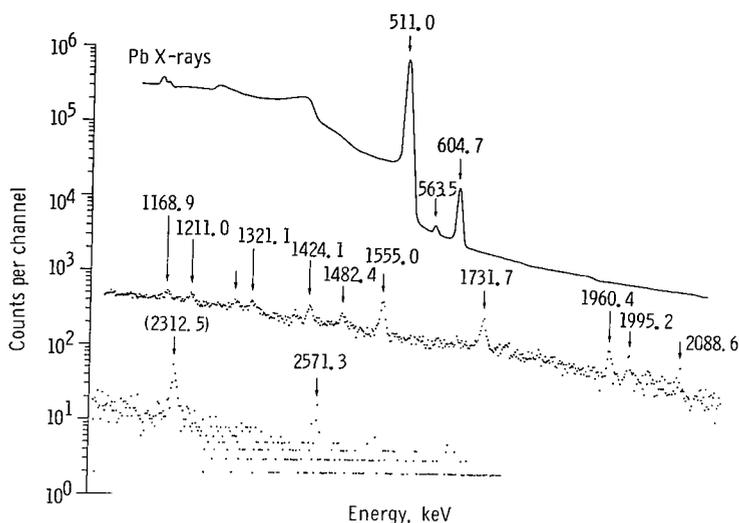


Figure 5. - Gamma-ray spectrum of  $^{134}\text{La}$ . Peaks due to contaminating  $^{140}\text{La}$  are indicated in parentheses. The energy scale graduation has been omitted and the spectrum folded twice to reduce length. Individual data points are replaced by a smooth line in part of the spectrum.

Energy, keV	Relative intensity
<sup>a</sup> 511.006±0.002	2200±310
563.5±0.3	6.7±1.0
604.7±0.1	100.0
1168.9±0.6	2.6±0.5
<sup>b</sup> 1211.0±0.7	2.4±0.5
<sup>c</sup> 1321.1±0.7	2.4±0.6
<sup>b</sup> 1424.1±0.5	3.9±0.7
<sup>b, c</sup> 1482.4±0.7	2.3±0.5
1555.0±0.3	8.6±1.3
1731.7±0.3	4.9±0.8
1960.4±0.6	2.0±0.4
1995.2±0.8	1.4±0.3
2088.6±1.5	0.8±0.3
<sup>b, d</sup> 2571.3±1.6	0.4±0.1

<sup>a</sup>Annihilation radiation. Energy value adopted from unpublished compilation by J. B. Marion, Univ. of Maryland.

<sup>b</sup>Not fitted into level scheme of fig. 11.

<sup>c</sup>Not reported in an earlier study (ref. 5) of the decay of  $^{134}\text{La}$ , but faintly visible in a spectrum published in that paper.

<sup>d</sup>Not positively identified as emitted by  $^{134}\text{La}$ .

be obtained. These values are given in table IV. The weighted average of these values,  $6.82 \pm 0.08$  minutes, is adopted as the half-life of  $^{134}\text{La}$ . The  $^{134}\text{La}$  source used for the determination of the half-life of the  $^{134}\text{La}$  annihilation radiation was prepared by bombarding anhydrous  $^{134}\text{BaCl}_2$ . In this source there was a small amount of  $^{136}\text{La}$  contaminant formed because the enriched  $^{134}\text{Ba}$  contained a small percentage of  $^{136}\text{Ba}$ , so correction had to be made for annihilation radiation due to  $^{136}\text{La}$ . No other contaminants were observed. The ratio of the intensity of the  $^{134}\text{La}$  annihilation radiation to the intensity of the 604.7-keV gamma ray was also determined from this experiment.

In an earlier experiment (ref. 5) two 7.6- by 7.6-centimeter NaI(Tl) scintillators were used to study coincidences between gamma rays emitted in the decay of  $^{134}\text{La}$  produced by 72-hour cerium 134 ( $^{134}\text{Ce}$ ). The actual spectra obtained were not published, but because they are relevant to the present experiment, they are reproduced herein as figures 6 to 10. A summary of the gamma-ray coincidence results is given in table VI.

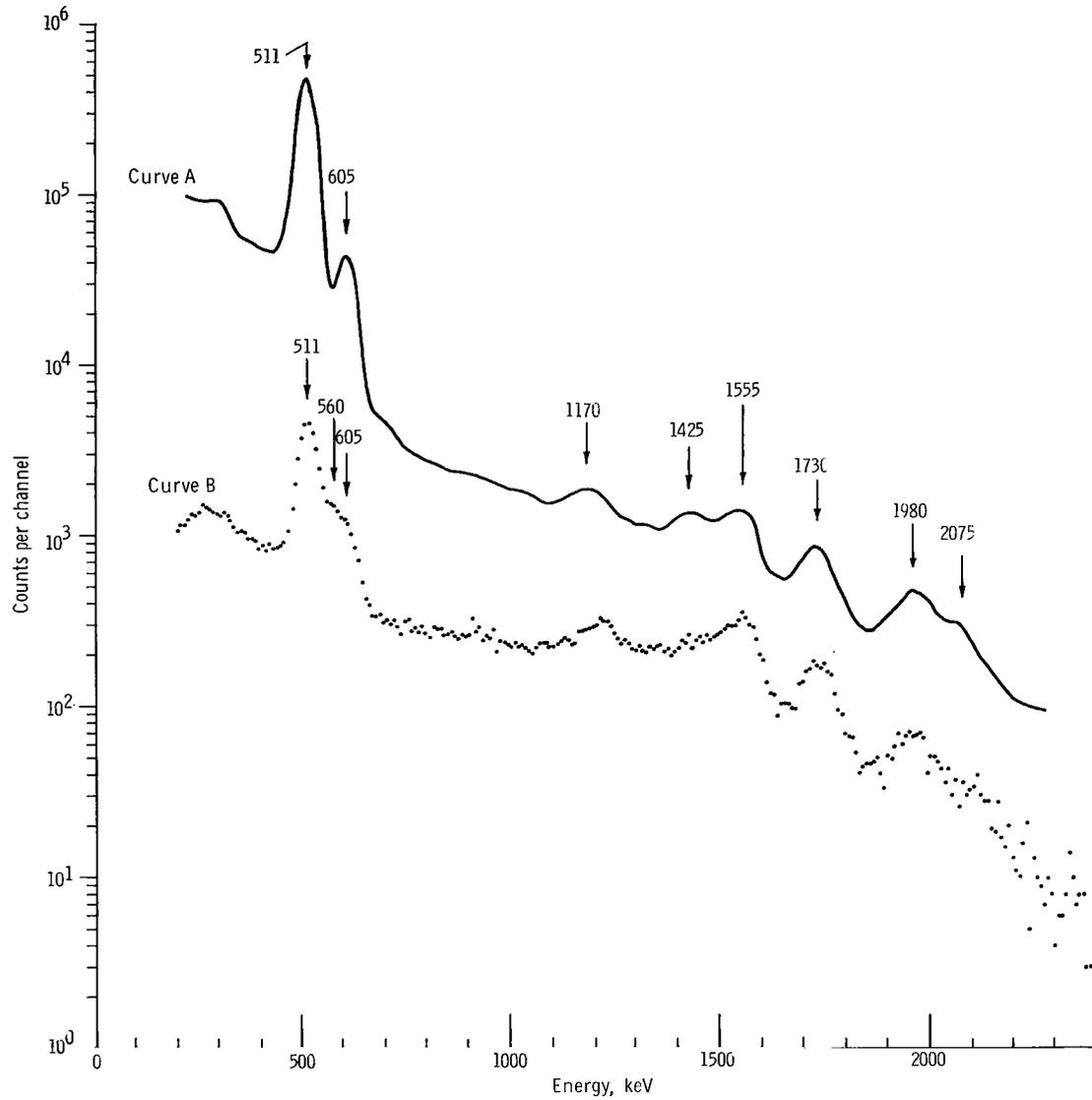


Figure 6. - Scintillation singles spectrum of gamma rays from  $^{134}\text{La}$  (curve A) and spectrum of gamma rays in coincidence with window at 605 keV (curve B).

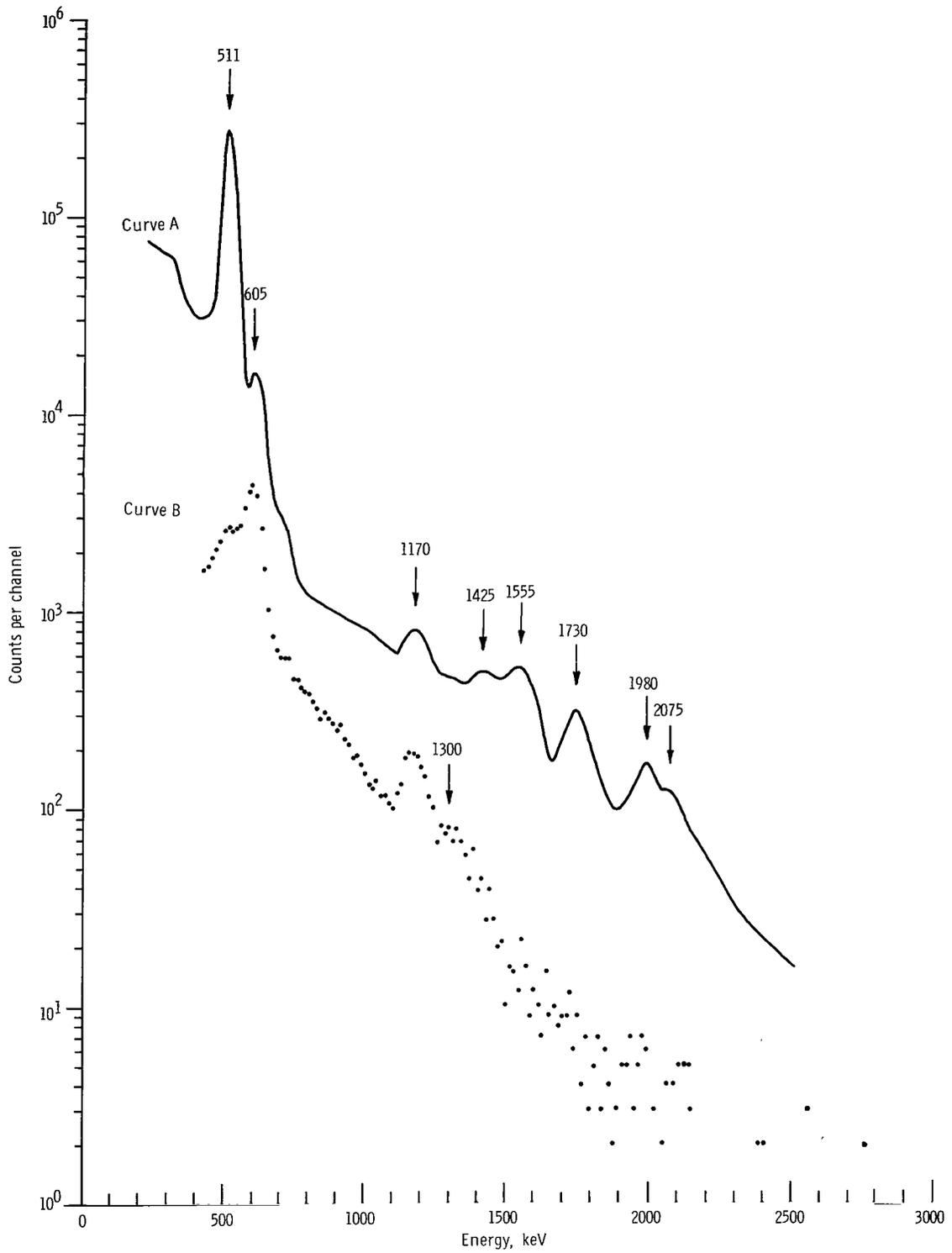


Figure 7. - Scintillation singles spectrum of gamma rays from  $^{134}\text{La}$  (curve A) and spectrum of gamma rays in coincidence with window at 1170 keV (curve B).

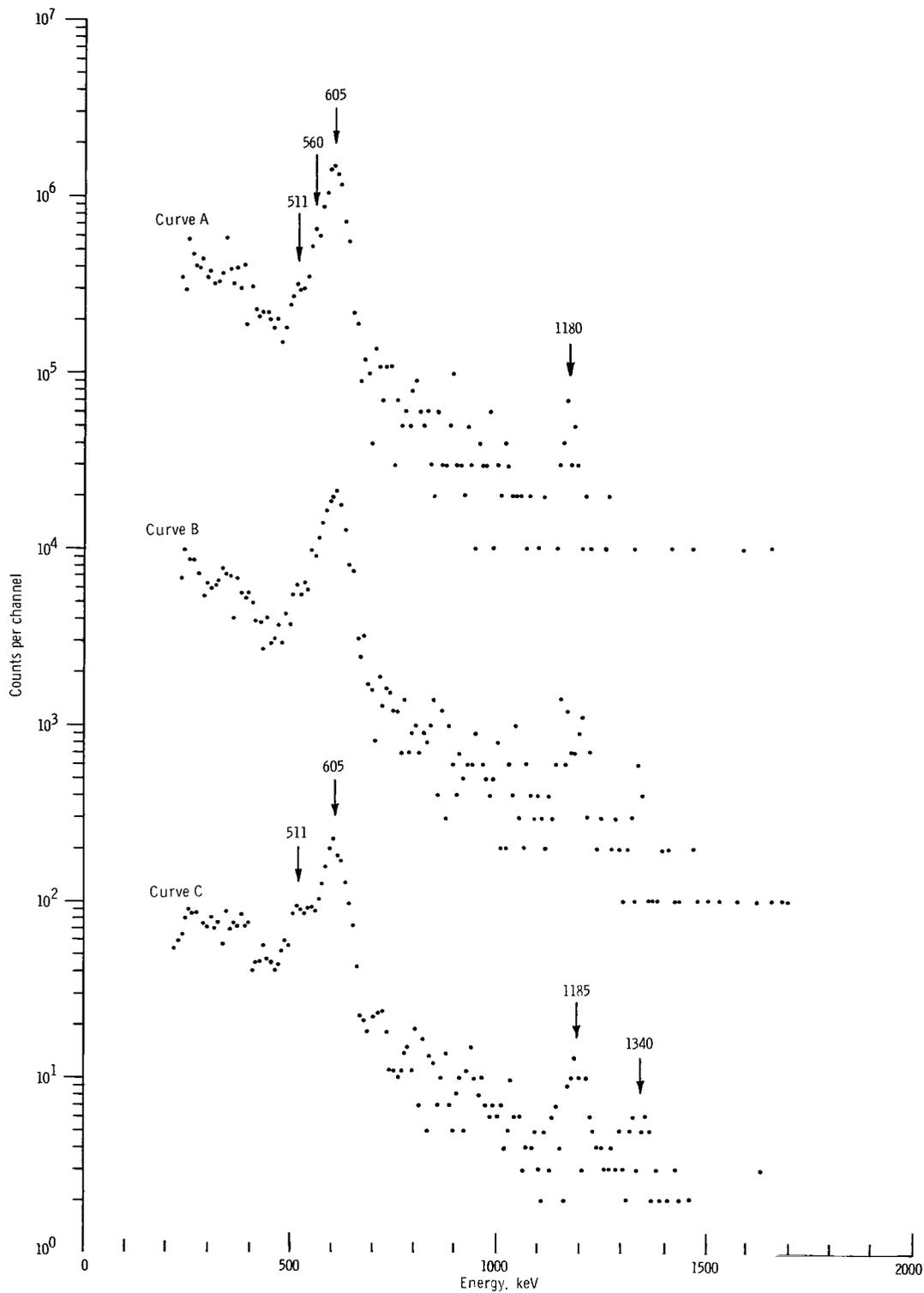


Figure 8. - Scintillation spectrum of  $^{134}\text{La}$  gamma rays in coincidence with window at 1425 keV (curve A), spectrum of gamma rays in coincidence with window at approximately 1300 keV (curve B), and spectrum of gamma rays in coincidence with window at 1170 keV (curve C). For clarity in presentation, data in curve A have been multiplied by  $10^4$ , and data in curve B by  $10^2$ .

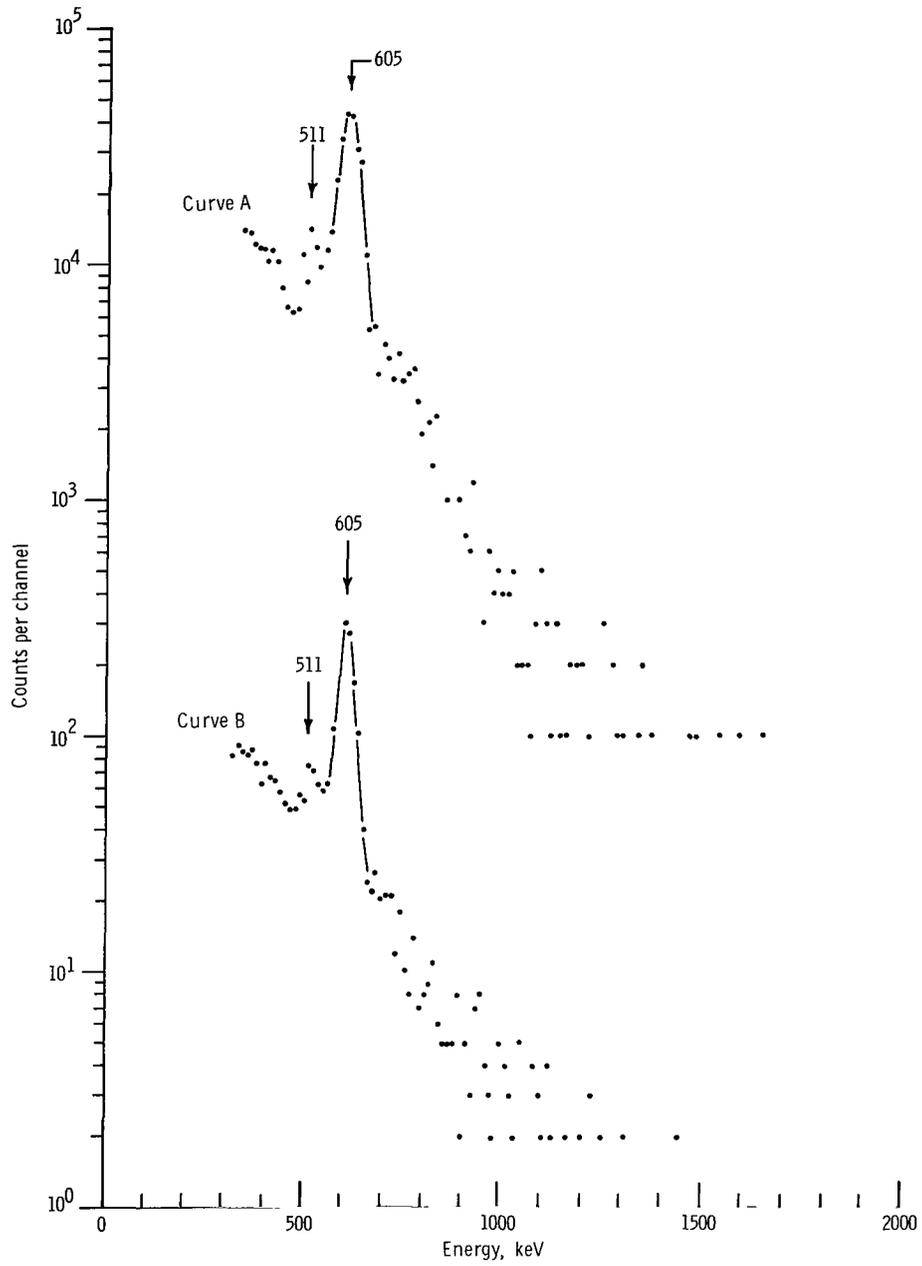


Figure 9. - Scintillation spectrum of  $^{134}\text{La}$  gamma rays in coincidence with window at 1730 keV (curve A) and spectrum of gamma rays in coincidence with window at 1555 keV (curve B). For clarity in presentation, data in curve A have been multiplied by  $10^2$ .

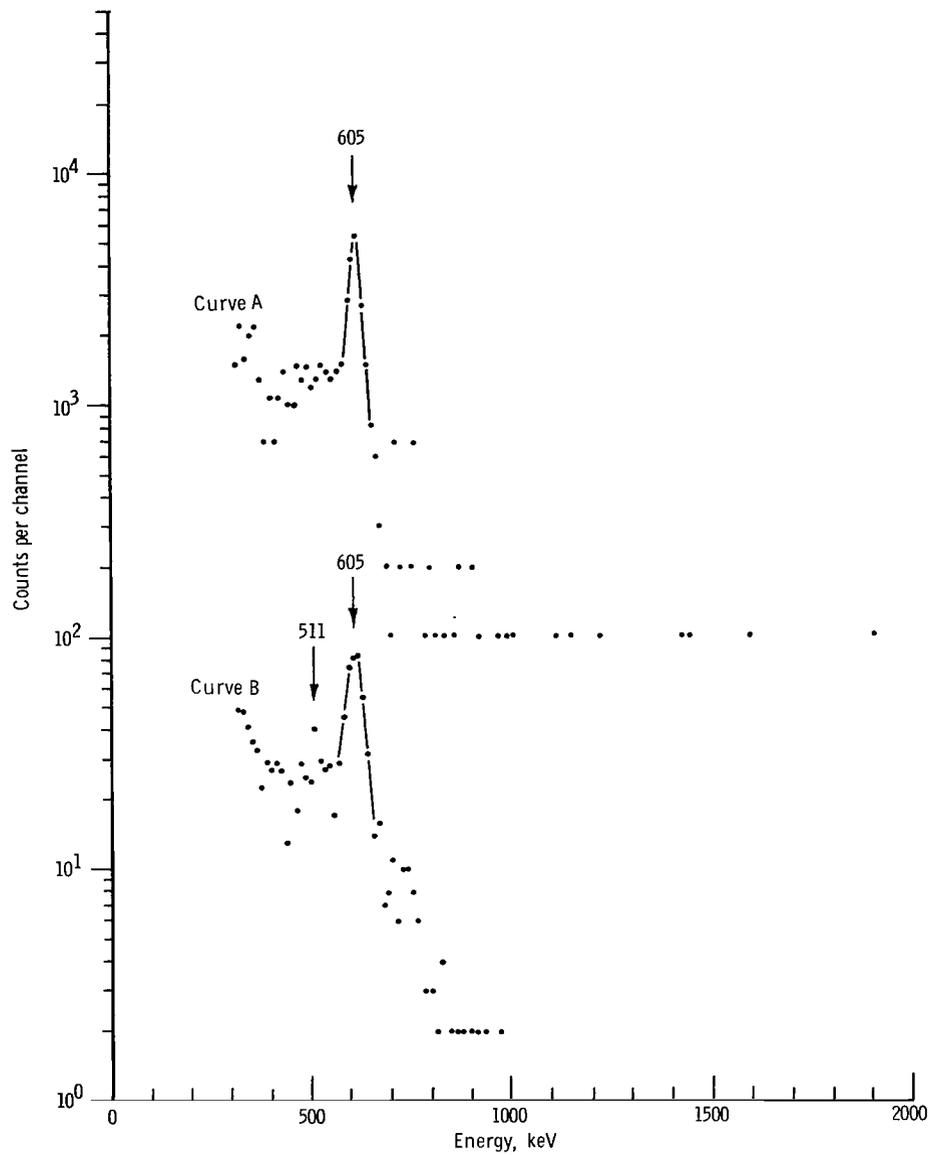


Figure 10. - Scintillation spectrum of  $^{134}\text{La}$  gamma rays in coincidence with window at 2100 keV (curve A) and spectrum of gamma rays in coincidence with window at 1980 keV (curve B). For clarity in presentation, data in curve A have been multiplied by  $10^2$ .

TABLE VI. - SUMMARY OF COINCIDENCE EXPERIMENTS ON  
GAMMA RAYS FROM  $^{134}\text{La}$

Gamma ray seen, keV	Gate gamma ray, keV							
	605	1170	~1300	1425	1555	1730	1980	2100
<sup>a</sup> 511	Y <sup>b</sup>	W	W	W	W	W	N	N
560	Y	?	W	W	N	N	N	N
605	W	Y	Y	Y	Y	Y	Y	Y
1170	W	Y	W	W	N	N	N	N
1300	N	W	N	N	N	N	N	N
1425	W	N	N	N	N	N	N	N
1555	Y	N	N	N	N	N	N	N
1730	Y	N	N	N	N	N	N	N
1980 (complex)	Y <sup>c</sup>	N	N	N	N	N	N	N
2075	Y	N	N	N	N	N	N	N

<sup>a</sup>Since the annihilation radiation is so strong, it is not surprising that some random counts persist in coincidence with gamma rays from levels fed only by electron capture.

<sup>b</sup>Y = yes, N = no, W = weak compared to intensity in singles.

<sup>c</sup>No shift in peak shape noted in coincidence.

Two noteworthy features of the spectrum in coincidence with the 605-keV gamma ray (fig. 6, curve B) are the apparent shift of the 1180-keV peak to about 1200 keV and the reduction in intensity of the 1425-keV gamma ray. These may mean that the 1211.0-keV gamma ray deexcites a level of  $^{134}\text{Ba}$  at 1815.7 keV, and that the 1424.1-keV transition populates a level of  $^{134}\text{Ba}$  higher than 604.7 keV.

From the coincidence results and from the results of the present study, the levels of  $^{134}\text{Ba}$  populated in the decay of  $^{134}\text{La}$  can be deduced. These levels are at  $604.7 \pm 0.1$ ,  $1168.2 \pm 0.3$ ,  $2159.7 \pm 0.3$ ,  $2336.4 \pm 0.3$ ,  $2489.3 \pm 0.8$ ,  $2565.1 \pm 0.6$ ,  $2599.9 \pm 0.8$ , and  $2693.3 \pm 1.5$  keV. The log ft values and relative intensities of the transitions from  $^{134}\text{La}$  were calculated by using the intensities of the gamma rays (table V), the maximum beta-ray energy of 2.67 MeV (ref. 5), and the same assumptions about electron-capture intensities as used for  $^{136}\text{La}$ . For comparison, figure 11 also shows the levels of  $^{134}\text{Ba}$  populated (refs. 17 to 19) in the decay of  $4^+ ^{134}\text{Cs}$ .

This level scheme (fig. 11) is slightly different from that proposed in reference 5 in that the 1321.1-keV gamma ray has been added. More accurate energy calibration has shown that the 1424.1-keV gamma ray cannot fit into the level scheme where proposed in reference 5. The 2565.1- and 2599.9-keV levels are shown dotted in figure 11 because the coincidence spectra do not unambiguously indicate that both the 1960.4- and 1995.2-keV gamma rays are in coincidence with the 604.7-keV gamma ray. The 1960.4- and

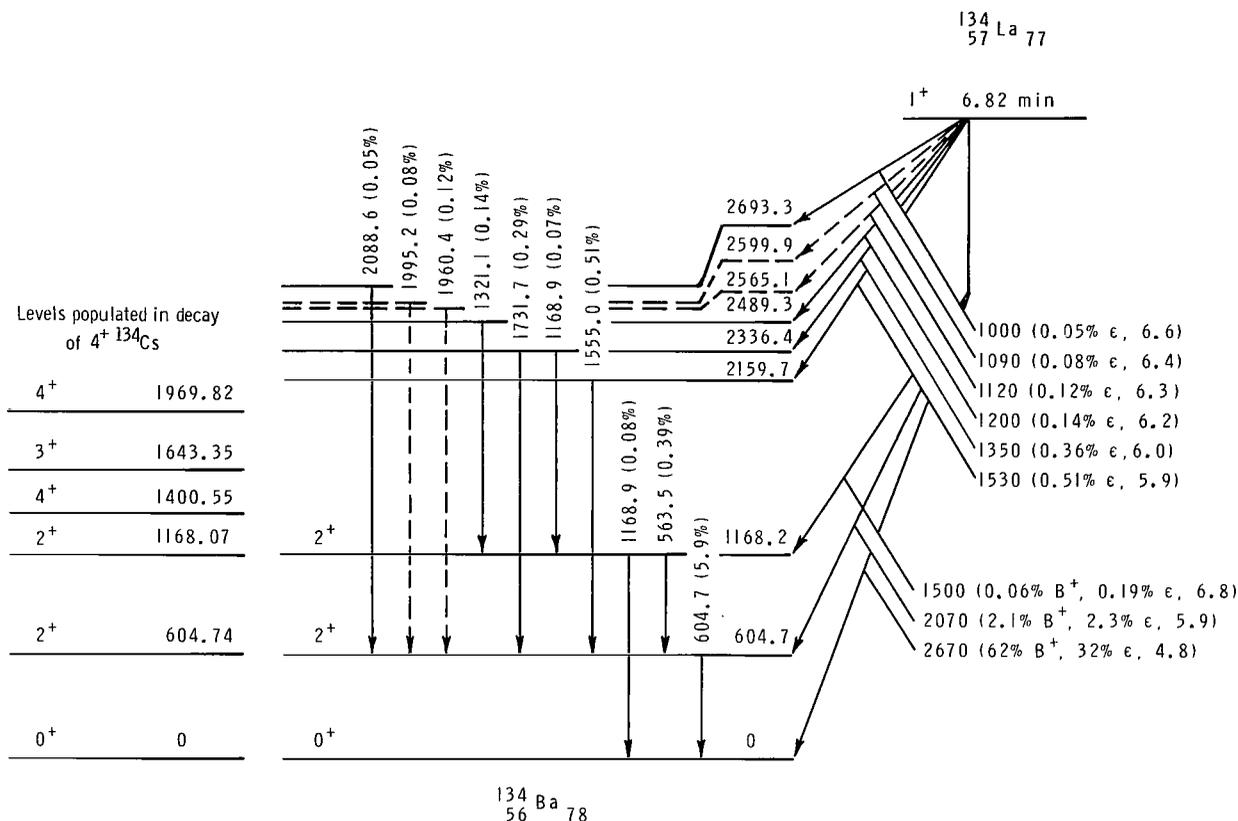


Figure 11. - Proposed level scheme of  ${}^{134}\text{Ba}$ . Energies are given in keV. Intensities of gamma rays and of beta-decay branches are given in percentage of  ${}^{134}\text{La}$  decays.

1995.2-keV gamma rays are not resolved in the coincidence spectrum (fig. 6, curve B); it may be that only one of these gamma rays is actually coincident with the 604.7-keV gamma ray. Note that the energy of the 2088.6 $\pm$ 1.5-keV gamma ray agrees within experimental error with the sum of the energies of the 1482.4 $\pm$ 0.7- and 604.7 $\pm$ 0.1-keV gamma rays. It is tempting to postulate a level of  ${}^{134}\text{Ba}$  at 2088 keV. Then it would be necessary to find another explanation for the result (figs. 6, curve B, and 10, curve A) that the 604.7-keV gamma ray is coincident with a gamma ray of about 2100 keV. One possibility is that there exists another gamma ray of about 2100 keV, in addition to the 2088.6-keV gamma ray observed in this study.

It is interesting to know the ratio of the intensities of the 1168- and 563-keV gamma rays which deexcite the second  $2^+$  excited state (denoted as  $2^{+1}$ ). This state is populated in the decay of both  $4^+ {}^{134}\text{Cs}$  and  $1^+ {}^{134}\text{La}$ . Reference 5 reported that the gamma-ray intensity ratio  $I(1168 \text{ keV})/I(563 \text{ keV})$  found in the decay of  ${}^{134}\text{La}$  was  $0.48 \pm 0.16$ , whereas the value of  $I(1168 \text{ keV})/I(563 \text{ keV})$  obtained (ref. 17) in the decay of  ${}^{134}\text{Cs}$  was  $0.23 \pm 0.03$ . In the present experiment these ratios were remeasured for both

TABLE VII. - ENERGIES AND  
RELATIVE INTENSITIES OF  
GAMMA RAYS FROM  $^{134}\text{Cs}$

Energy, keV <sup>a</sup>	Relative intensity
475.355	1.2±0.2
563.325	9.4±1.3
569.371	16.2±2.3
604.744	100
795.806	88±12
801.86	9.8±1.4
1038.61	1.2±0.2
1167.99	1.9±0.3
1365.08	3.5±0.5

<sup>a</sup>Energies are used only to  
identify gamma rays.  
Energy values are taken  
from ref. 18.

$^{134}\text{Cs}$  and  $^{134}\text{La}$ , and different values were again obtained. A source of  $^{134}\text{Cs}$  was counted with the same spectrometer and under the same conditions in which  $^{134}\text{La}$  was studied. Table VII lists the measured relative intensities of the gamma rays from  $^{134}\text{Cs}$ . Their agreement with published results (refs. 17 to 19) indicates that there are not systematic errors in the present experiment.

When gamma-ray intensities from table VII are used, the ratio  $I(1168 \text{ keV})/I(563 \text{ keV})$  is  $0.20 \pm 0.04$ . However, for gamma rays emitted by  $^{134}\text{La}$ , the ratio  $I(1168 \text{ keV})/I(563 \text{ keV})$  is  $0.39 \pm 0.09$ . The branching ratio for the deexcitation modes of a state should be independent of how the level is populated. Hence, it is concluded that the peak observed at 1168 keV in the spectrum of  $^{134}\text{La}$  represents two transitions with very nearly the same energy. The existence of a second 1168-keV gamma ray is consistent with the coincidence results (figs. 7 and 8), and this gamma ray fits nicely between the levels at 2336.4 and 1168.2 keV. Since the gamma-ray intensity ratio measured in the decay of  $^{134}\text{La}$  includes both 1168-keV transitions, the following branching ratio measured in the decay of  $^{134}\text{Cs}$  is adopted:  $I(2^{+'} \rightarrow 0^{+})/I(2^{+'} \rightarrow 2^{+}) = 0.20 \pm 0.04$ . Then it may be concluded that  $0.51 \pm 0.16$  of the intensity of the 1168-keV peak observed in the decay of  $^{134}\text{La}$  is due to the transition from the 1168.2-keV level of  $^{134}\text{Ba}$  to the ground state.

## DISCUSSION

The present study has located new low-lying states of  $^{136}\text{Ba}$  and has confirmed or clarified earlier results on the low-lying states of  $^{134}\text{Ba}$ .

In agreement with the recently announced result (ref. 5), the gamma-ray spectra recorded in this study reveal no evidence of a hypothesized  $0^+$  vibrational triplet member in  $^{134}\text{Ba}$ . In this study the gamma-ray branching ratio for the deexcitation of the  $2^{+}$  excited state of  $^{134}\text{Ba}$  at 1168 keV has been determined to be  $I(2^{+} \rightarrow 0^+)/I(2^{+} \rightarrow 2^{+}) = 0.20 \pm 0.04$ . On the basis of the conversion electron studies of reference 17, the 563- and 1168-keV transitions are assumed to be pure electric quadrupole radiations (E2). Since internal conversion of these transitions may be neglected (ref. 20), the ratio of the reduced transition probabilities for the two modes of deexcitation of the second excited state of  $^{134}\text{Ba}$  is

$$\left[ \frac{B(E2; 2^{+} \rightarrow 0^{+})}{B(E2; 2^{+} \rightarrow 2^{+})} \right] = \left[ \frac{I(1168.2 \text{ keV})}{I(563.5 \text{ keV})} \right] \left( \frac{563.5}{1168.2} \right)^5 = 0.005 \pm 0.001$$

The analogous ratios, computed from the data of references 21 and 22, are 0.020 for xenon 134 ( $^{134}\text{Xe}$ ) and 0.0015 for xenon 132 ( $^{132}\text{Xe}$ ).

A particularly interesting result of this study is the discovery of one, but only one, excited state of  $^{136}\text{Ba}$  at about twice the energy of the first excited state. The value of the log ft for the beta decay from  $1 + ^{136}\text{La}$  to the 1578.9-keV state suggests that the decay is allowed, and hence, that this state is  $0^+$ ,  $1^+$ , or  $2^+$ . No crossover transition from this level to the ground state is observed in the gamma-ray spectrum; the upper limit on the intensity of the crossover gamma ray is 0.2 percent of the intensity of the 818.5-keV gamma ray. Of course, if the level is  $0^+$ , no crossover gamma ray is possible. Like  $^{136}\text{Ba}$ , each of the nearby nuclei,  $^{134}\text{Xe}$ ,  $^{132}\text{Xe}$ , and  $^{134}\text{Ba}$ , has an excited state at 1.9 times the energy of the first  $2^+$  state (fig. 12) (refs. 14, 15, 17 to 19, and 21 to 23). In each of the neighboring nuclei, this level is identified as  $2^+$ , so it seems reasonable to believe that the 1578.9-keV level of  $^{136}\text{Ba}$  is also  $2^+$ . However, argument from systematics is weakened by the following occurrences: the recent discovery (G. C. Morrison, private communication) of a  $\approx 1550$ -keV level of  $^{136}\text{Ba}$ , which reduces the striking similarity between the low-lying levels of  $^{136}\text{Ba}$  and those of the neighboring nuclei in figure 12 and the report (ref. 24) that  $^{138}_{58}\text{Ce}_{80}$  has a  $0^+$  excited state at 1.9 times the energy of the  $2^+$  first excited state. If the 1578.9-keV level of  $^{136}\text{Ba}$  is assumed to be  $2^+$ , an upper limit on the ratio of the reduced transition probabilities for the two possible modes of deexcitation of this state can be estimated. Again, when internal conversion is neglected, this upper limit is

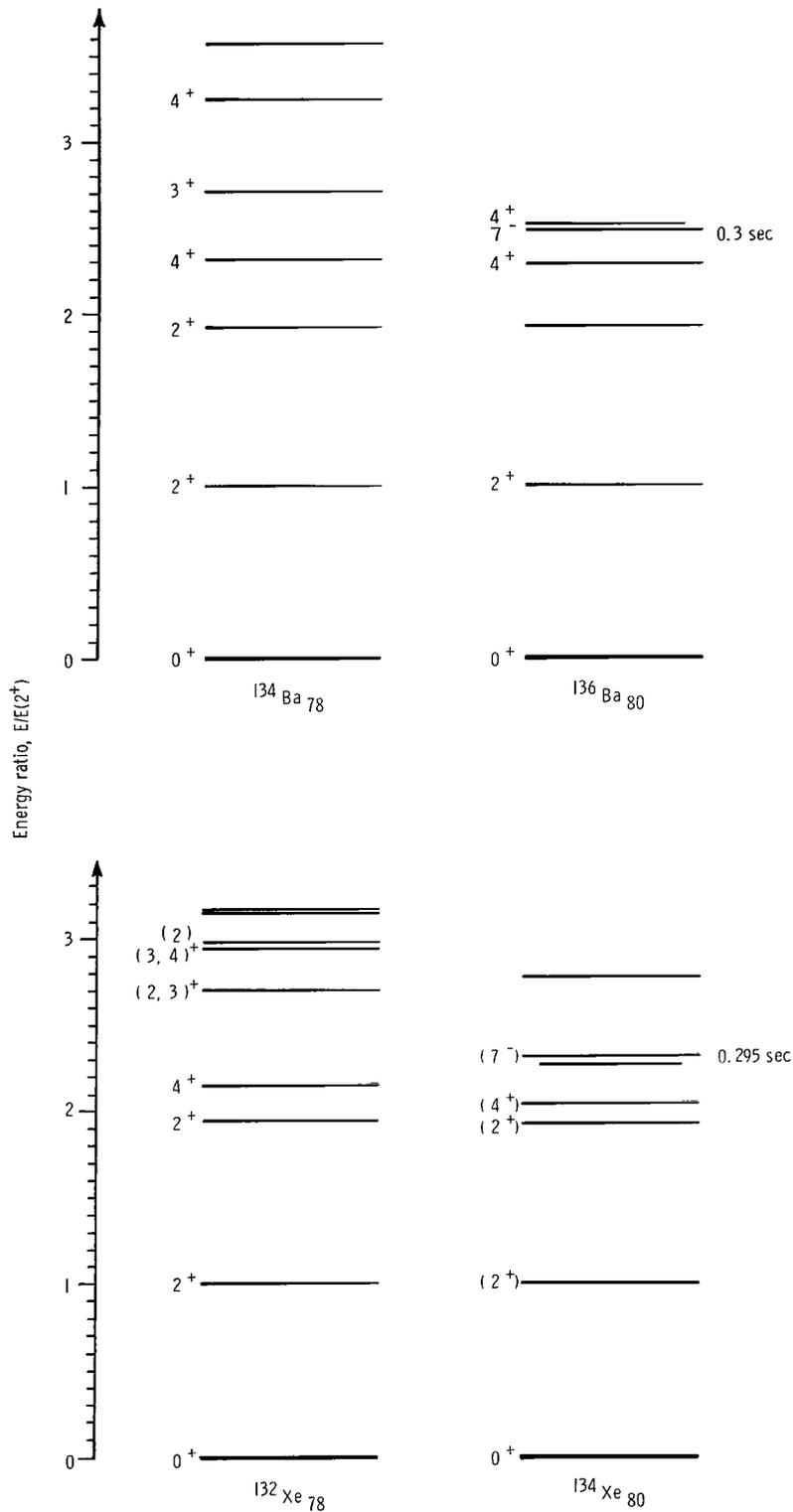


Figure 12. - Level schemes of neighboring even-even nuclei  $^{136}\text{Ba}$ ,  $^{134}\text{Ba}$ ,  $^{134}\text{Xe}$ , and  $^{132}\text{Xe}$ . Drawings are made to the same energy scale. Data are from references 14, 15, 17 to 19, and 21 to 23 and the present study.

$$\left[ \frac{B(E2; 2^{+'} \rightarrow 0^{+})}{B(E2; 2^{+'} \rightarrow 2^{+})} \right] \leq \left[ \frac{I_{\max}(1578.9 \text{ keV})}{I(760.4 \text{ keV})} \right] \left( \frac{760.4}{1578.9} \right)^5 = 0.0004$$

## CONCLUDING REMARKS

An experimental study has been made of the beta decay of  $^{136}\text{La}$  and  $^{134}\text{La}$  to  $^{136}\text{Ba}$  and  $^{134}\text{Ba}$ , respectively. New low-lying excited states of  $^{136}\text{Ba}$  have been located, and earlier results on the low-lying states of  $^{134}\text{Ba}$  have been confirmed or clarified. The ratio of the intensities of transitions depopulating the second excited state of  $^{134}\text{Ba}$  has been measured unambiguously for the first time. No evidence has been found to indicate that either  $^{136}\text{Ba}$  or  $^{134}\text{Ba}$  possesses all three members of a possible "vibrational triplet" of states at about twice the energy of the first excited state.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, September 6, 1968,  
129-02-04-06-22.

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